High Flux Isotope Reactor: Forged by safety, fueled by discovery

As night descends on the Department of Energy's Oak Ridge National Laboratory, the High Flux Isotope Reactor (HFIR) bursts with activity. A rigorous 24-day fuel cycle concludes and neutron production pauses at the lab's research reactor where neutrons help unravel the secrets of materials and energy.

The reactor bay comes alive with the men and women who guard the frontiers of scientific research and discovery at HFIR — all night and all day for about the next two weeks during this typical refueling and maintenance outage.

With surgical precision, reactor operators work from a motorized bridge with 30-foot hand tools designed to navigate intricate spaces on the submerged reactor core. The entire pool area, about the size of an Olympic swimming pool and 17 feet deep, glows bright sapphire blue from the Cherenkov radiation effect. This phenomenon happens when charged particles from radioactive decay travel faster than light in water. The water in the pool serves the essential functions of cooling and radiation shielding.

During a maintenance outage, HFIR crews move with the synchronicity of an operating room, each entering the bay at the precise time a certain skillset is needed. Operators, radiological control technicians and quality assurance specialists collaborate to dismantle, rebuild, refuel and prepare the reactor for restart. They handle irradiated materials, add new experiment samples to HFIR's core and package radiological materials for transport. They load radiological packages in everything from small protective casings the size of a short pencil that ride 100 feet to the Radiochemical Engineering Development Center for isotope production to giant dog-bone-shaped casks that ride hundreds of miles on semitruck beds for offsite storage.

Two weeks later, at the end of the outage, the operating cycle begins again. HFIR's reactor operators restart the reactor, fine-tuning reactivity, testing water chemistry, checking valves throughout the facility and keeping a constant pulse on the reactor's safety systems — day and night. Operations supervisors play a central role, managing activities, directing critical tasks and training the next generation of reactor operators, most of whom graduated from the U.S. Navy's nuclear program.

The Navy's rigorous 18-month accelerated program in math, physics and engineering produces highly skilled, trusted operators who typically move on to ensuring safe operations for nuclear-powered submarines and aircraft carriers.

Then they come to HFIR, bringing their culture of discipline and safety to bear on the operation of this invaluable U.S. resource.

Core of safety at HFIR

With equally rigorous standards, safety at HFIR involves multiple roles. Key players in safety at HFIR, known as radiological control technicians (RCTs), interact at all levels, working hand-in-hand with reactor operators and reporting safe conditions to management while ensuring safe practices in daily operations. RCTs assess potential hazards and establish radiological conditions, communicating with staff throughout the days and nights by way of map postings and briefings.

Nuclear safety analysts at HFIR continually assess hazards, evaluating processes and equipment to prevent incidents and prepare for necessary responses. ORNL's Research Reactors Division ensures that

experimental samples loaded into the core pose no risks to the safety of the reactor or personnel through stringent processes and procedures, securing competitive science and innovation for the nation.

Roughly the size of a 30-gallon drum with enough energy to power a small city for several days, HFIR's 85-megawatt core, fueled with uranium-235, is one of two reactor-based neutron sources in the world that can produce such a high flux, or continual flow, of neutrons.

HFIR's core assembly design includes an 8-foot diameter pressure vessel submerged in the reactor pool, which helps provide radiation shielding and cooling. Nearly 16,000 gallons of water per minute flow through the pool from an independent primary coolant system, accomplishing the majority of the cooling work. The core's design also includes a beryllium reflector that helps maintain reactor criticality by reflecting stray neutrons back to the core. Redundant safety mechanisms include control plates that can independently shut down the reactor, if needed.

Although the control room appears similar to the way it did when HFIR first operated, continual updates and maintenance throughout the years keep monitoring and control performance at a high level so that personnel can ensure the reliability and safety of the facility.

Neutrons: A discovery powerhouse

Once the operators refuel the reactor and the next fuel cycle begins, hundreds of top scientists and researchers from around the world come to HFIR to gain knowledge no other research techniques provide. As the most powerful reactor-based source of neutrons in the Western hemisphere, HFIR helps the U.S. remain competitive with other nations in neutron science research.

The high flux, or flow, of neutrons, needed to produce isotopes, continues to achieve the facility's original mission, which began in 1965 with HFIR's first criticality. At the time, HFIR fulfilled a national need for producing "heavy" elements such as plutonium and californium for research, industrial and medical applications.

However, discovery research at HFIR also plays landmark roles in a range of science and technology. One of two neutron scattering facilities in North America, HFIR allows scientists to unlock mysteries of matter not accessible any other way. Combined with ORNL's Spallation Neutron Source (SNS), the two facilities form a discovery powerhouse that continually recharges America's global leadership in discovery science year after year, decade after decade. Plans for a third neutron source at ORNL, the Second Target Station, are underway.

Today, HFIR has four major missions: neutron scattering research using its suite of 12 state-of-the-art instruments; production of medical, industrial and research isotopes, many of which can be made nowhere else in the world; materials irradiation testing; and neutron activation analysis to examine trace elements.

Its primary mission, neutron scattering, provides researchers with a technique to explore atomic-scale dynamics in experimental samples as small as magnetic moments in quantum materials and big as jet engines. The 12 scientific instruments connected to HFIR's powerful core allow users to experiment with materials at the atomic scale, resulting in breakthrough discoveries and paving the way for life-changing technologies.

Because of neutrons' unique properties — deeply penetrating, nondestructive, and able to "see" light elements such as hydrogen and lithium — they provide insights no other research technique can. Discoveries made possible using neutrons help unravel the secrets of materials and energy, leading to the development and improvements of everyday products like hard drives, medicines and infrastructure such as bridges and cables. Scientists use the neutrons produced by HFIR to study physics, chemistry, materials science, engineering and biology, resulting in advances in many areas that improve daily life.

Discoveries at HFIR continue to make impacts for NASA space missions, the detection of dangerous materials, cancer treatment centers, medical advancements for Alzheimer's and other neurodegenerative diseases, industrial and agricultural processes, advanced 3D printing applications, pharmaceutical and geochemistry studies and consumer technologies.

Examples of discovery science at HFIR:

- Biochemist David Baker, a 2024 recipient of the Nobel Prize for Chemistry, turned to HFIR for information he couldn't get anywhere else. Read story here.
- Neutron research at HFIR revealed the cause of the Arecibo telescope collapse in Puerto Rico. Read story here, watch video here.
- A researcher from The University of Oklahoma College of Dentistry used neutron scattering at HFIR to invent a more durable, antibacterial dental resin. Read story here and watch video here.
- A group of scientists used neutron scattering techniques to investigate a relatively new functional material called a Weyl semimetal, which could allow electricity to flow more efficiently in future electronic devices. Read story here.
- Researchers designed and accurately characterized a novel polymer that is as effective as natural proteins in transporting protons through a membrane. This discovery could help make batteries and water purification systems more efficient. Read story here.
- NASA scientist Andrew Needham used a neutron imaging capability at HFIR to study moon rock samples brought back from the Apollo missions. Read story here.

Planning is underway to extend the Cold Guide Hall, the location of eight of HFIR's 12 neutron scattering instruments. Once the extension is complete, the guide hall will have an additional 5,600 square feet to provide space for new cold neutron instruments and to develop new capabilities.

Isotopes at HFIR

Today, still operating based on its original mission, HFIR produces 70% of the world's supply of californium-252. Among other critical uses, this isotope provides the power needed to start nuclear reactors. Isotopes from HFIR help a range of industries around the world identify potential deposits of oil and gas, provide cancer therapy and detect pollutants in the environment, explosives in luggage and illicit materials in cargo for port security.

The impacts of science from HFIR include the development of medical isotopes and elements for the periodic table, fuels and materials for advanced reactors and other energy security technologies, new medicines and biosecurity, 3D printing, forensic science and space exploration.

Likewise, ORNL-produced plutonium-238 helped power Perseverance on Mars. HFIR also leads America's efforts to establish secure domestic production of enriched uranium to help develop advanced materials

and additive manufacturing capabilities for national security uses, such as advanced welding methods for the steel used in building U.S. nuclear submarines.

HFIR's bright future: Projects and upgrades

In 2014, the American Nuclear Society designated HFIR as a Nuclear Historic Landmark in recognition of its vital role in the history of the nuclear age and its continued importance to the U.S. for neutron scattering research, isotope production and national security. In 2017, the International Atomic Energy Agency (IAEA) designated ORNL as an International R&D Hub because of HFIR's continued importance for post-irradiation testing of materials, neutron scattering and processing of radioisotopes. The IAEA designation made the U.S. one of only four countries identified for unique capabilities and excellence in nuclear research.

Looking forward, to ensure operations to the end of the century, including a return to operating at the reactor's designed power of 100 megawatts, plans are underway to replace HFIR's beryllium reflector and pressure vessel. The beryllium reflector sends most stray neutrons back into the core during reactor operation, but due to the intensity of the flux, the reflector must be replaced about every 20 years.

In the 1980s, engineers found HFIR's carbon steel pressure vessel, or core container, more brittle than anticipated as an effect of the intense neutron environment. At that time, they reduced the reactor's operating power from 100 megawatts to 85 megawatts to slow the embrittlement and increase the reactor's operating lifetime. The long-term effects of continual bombardment cause embrittlement of the pressure vessel, requiring its replacement before its estimated end of life. However, plans are to replace the vessel well before then.

Given HFIR's importance in a myriad of critical applications, the beryllium reflector replacement and pressure vessel replacement project will ensure long-term availability of this vital national resource.

HFIR embodies the spirit of innovation. HFIR's operational excellence, living commitment to safety and dedication to neutron scattering and isotope production make it a beacon for discovery science. Its historic scientific impacts for the nation and the world set the standard for vital national resources that can adapt to new challenges and meet demands for solving difficult problems. Its legacy of impactful research and remarkable discoveries prove that HFIR will undoubtedly play a critical role in future science.

The best is yet to come.

HFIR is a DOE Office of Science user facility.

UT-Battelle manages ORNL for DOE's Office of Science, the single largest supporter of basic research in the physical sciences in the United States. The Office of Science is working to address some of the most pressing challenges of our time. For more information, visit energy.gov/science. — *Sumner Brown Gibbs*